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Preliminary Examination of Ethanol Fuel Effects on EPA's R-factor for Vehicle Fuel Economy

June 2013

Prepared by

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PRELIMINARY EXAMINATION OF ETHANOL FUEL EFFECTS ON EPA'S R-FACTOR FOR VEHICLE FUEL ECONOMY

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) supported a test program from 2007 through 2012 to evaluate the potential impacts of intermediate ethanol blends (also known as mid-level blends) on legacy vehicles and other engines. The purpose of the program was to assess the viability of using intermediate ethanol blends as a contributor to meeting national goals for the use of renewable fuels. Appendix A lists a bibliography of related studies. The catalyst durability program involved aging and emissions testing vehicles on a range of ethanol blends. The study was completed in 2011 and a final report issued shortly after.[*]

This report describes a preliminary analysis of the fuel economy data from the catalyst durability study, to determine the proper value for the R factor which is called out in the Code of Federal Regulations (CFR) for computing vehicle fuel economy on the certification cycle. The fuel economy equation that is specified in CFR for gasoline-fuelled vehicles is based on a carbon mass balance (CMB) approach to determine the amount of fuel consumed during the test by measuring the carbon-bearing emissions that are produced; however, it also incorporates a scaling factor (R factor) based on the net heating value of the fuel and the sensitivity of fuel economy to changes in the heating value.[†,‡] The impact of the R factor is a fixed ratio in the resultant fuel economy that is dependent upon fuel properties other than those required for a typical CMB calculation. This equation was put in place in 1988 to correct for differences between certification fuels to address corporate average fuel economy (CAFE) credit issues associated with fuel property variations. The algorithm adjusts the calculated fuel economy to compute what would have been measured had the 1975 certification fuel been used for the test. The R factor was defined as the sensitivity of the fuel economy result to changes in fuel energy content. When R equals 1.0, the fuel economy change exactly tracks the energy density difference between the fuels. If R is less than 1.0, the fuel economy change is smaller than the change in energy density. The R factor was defined to be 0.6 based on tests using 1980s vehicles. Since that time, the Auto/Oil test program has established that the R factor for 1990s vehicles is higher (about 0.93).[§] More recently EPA analyzed the EPAct/V2/E-89 dataset[**] to compute the R factor, resulting in an average of 0.82 to 0.86.[††] It is important to note that the EPAct/V2/E89 test program used the LA92 test cycle, a cycle known to contain more aggressive accelerations than the FTP.[‡‡]

To date, EPA has only required emissions and fuel economy testing of gasoline vehicles with a certification fuel that does not contain ethanol. However in 2013 EPA issued a Proposed Rule seeking comment on the establishment of an emissions certification fuel containing ethanol, such as E10 or E15.[§§] Calculating modern vehicle fuel economy with the existing CFR equation with an R factor of 0.6 when ethanol blends are used produces significant errors. For the catalyst durability program, a straightforward

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[*] West, Brian H., Scott Sluder, Keith Knoll, John Orban, Jingyu Feng, *Intermediate Ethanol Blends Catalyst Durability Program*, ORNL/TM-2011/234, February 2012, available at http://info.ornl.gov/sites/publications/Files/Pub31271.pdf

[†] *Federal Register* Vol. 51(206), Friday, October 24, 1986, pp. 37844–37852.

[‡] 40 CFR Pt. 600.

[§] Albert Hochhauser et al., "Fuel Composition Effects on Automotive Fuel Economy—Auto/Oil Air Quality Improvement Research Program," SAE paper 930138, SAE International, Warrendale, Pennsylvania, March 1993.

[**] "EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards, Final Report on Program Design and Data Collection", Report Number EPA-420-R-13-004, March 2013

[††] Aron Butler, David Good, Arvin Mitcham, "Analysis of the Effects of Changing Fuel Properties on the EPA Fuel Economy Equation and R-Factor," Memorandum to Tier 3 Docket #EPA-HQ-OAR-2011-0135, available at http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2011-0135-0604

[‡‡] Keith Knoll, Brian West, Wendy Clark, Ronald Graves, John Orban, Steve Przesmitzki, Timothy Theiss, *Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1—Updated*, NREL/TP-540-43543, ORNL/TM-2008/117, February 2009, available at http://info.ornl.gov/sites/publications/Files/Pub12154.pdf

[§§] *Federal Register* Vol. 78 (98), Tuesday, May 21, 2013

CMB approach was used to compute fuel economy, thereby allowing a straightforward evaluation of the impact of ethanol content on fuel economy. However, if an ethanol-containing fuel is to become the new certification fuel for light-duty vehicles, consistent application of the CFR equation needs to be considered for the benefit of manufacturers' CAFE compliance.

Analysis of city cycle Federal Test Procedure (FTP) fuel economy test results and fuel analyses from the catalyst durability study indicates that the average R-factor for modern vehicles is very close to unity at about 0.94±0.04. This result is very similar to the results of the 1993 Auto/Oil test program.[*] Future work should examine other drive cycles, and advanced vehicle technologies which may reveal sensitivities to properties other than heating value.

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[*] Albert Hochhauser et al., SAE paper 930138, March 1993.

1. BACKGROUND

The Energy Independence and Security Act of 2007[*] requires significant increases in the nation's use of renewable fuels to meet its transportation energy needs. The law established a renewable fuel standard that requires the nation to use 36 billion gallons of renewable fuel per year in its vehicles by 2022. Given that ethanol is the most widely used renewable fuel in the United States and production is expected to continue to grow over the next several years, ethanol will likely make up a significant portion of the renewable fuels required by the standard. Most of the ethanol used in the United States is blended with gasoline to create E10—gasoline with up to 10% ethanol. In 2010 and 2011 the EPA approved the use of E15 in 2001 and newer light-duty vehicles[†,‡] citing a number of studies, including the DOE catalyst durability study.[§] (Appendix A lists a full bibliography of related intermediate ethanol blend studies.)

During the normal course of the catalyst durability study, vehicles were periodically tested for emissions and fuel economy on the light-duty Federal Test Procedure, or FTP-75.[**] As such, a large number of fuel economy test results on a range of fuels are available for analysis. Details on vehicle selection, test protocol, and fuels used can be found in the catalyst durability study final report.

This report describes a preliminary analysis of the fuel economy data from the catalyst durability study, to determine the proper value for the R factor which is called out in the Code of Federal Regulations (CFR) for computing vehicle fuel economy on the certification cycle. The fuel economy equation that is specified in CFR for gasoline-fuelled vehicles is based on a carbon mass balance (CMB) approach to determine the amount of fuel consumed during the test by measuring the carbon-bearing emissions that are produced; however, it also incorporates a scaling factor (R factor) based on the net heating value of the fuel and the sensitivity of fuel economy to changes in the heating value.[††,‡‡] The impact of the R factor is a fixed ratio in the resultant fuel economy that is dependent upon fuel properties other than those required for a typical CMB calculation. This equation was put in place in 1988 to correct for differences between certification fuels to address corporate average fuel economy (CAFE) credit issues associated with fuel property variations. The algorithm adjusts the calculated fuel economy to compute what would have been measured had the 1975 certification fuel been used for the test. The R factor was defined to be 0.6 based on tests using 1980s vehicles. Since that time, the Auto/Oil test program has established that the R factor for 1990s vehicles is higher (about 0.93).[§§] More recently EPA analyzed the EPAct/V2/E-89 dataset[***] to compute the R factor, resulting in an average of 0.82 to 0.86.[†††] It is important to note that

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[*] H.R. 6 (110th): Energy Independece and Security Act of 2007, 12/19/2007, available at: http://www.govtrack.us/congress/bills/110/hr6/text

[†] *Federal Register*, Vol. 75(213), Thursday, November 4, 2010, Notices.

[‡] *Federal Register*, Vol. 76(17), Wednesday, January 26, 2011, Notices.

[§] West, Brian H., Scott Sluder, Keith Knoll, John Orban, Jingyu Feng, *Intermediate Ethanol Blends Catalyst Durability Program*, ORNL/TM-2011/234, February 2012, available at http://info.ornl.gov/sites/publications/Files/Pub31271.pdf

[**] The FTP-75 is the basis of light duty vehicle "city" fuel economy. See http://www.epa.gov/nvfel/testing/dynamometer.htm

[††] *Federal Register* Vol. 51(206), Friday, October 24, 1986, pp. 37844–37852.

[‡‡] 40 CFR Pt. 600.

[§§] Albert Hochhauser et al., "Fuel Composition Effects on Automotive Fuel Economy—Auto/Oil Air Quality Improvement Research Program," SAE paper 930138, SAE International, Warrendale, Pennsylvania, March 1993.

[***] "EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards, Final Report on Program Design and Data Collection", Report Number EPA-420-R-13-004, March 2013

[†††] Aron Butler, David Good, Arvin Mitcham, "Analysis of the Effects of Changing Fuel Properties on the EPA Fuel Economy Equation and R-Factor," Memorandum to Tier 3 Docket #EPA-H!-OAR-2011-0135, available at http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2011-0135-0604

the EPAct/V2/E89 test program used the LA92 test cycle, a cycle known to contain more aggressive accelerations than the FTP.[*]

Calculating modern vehicle fuel economy with the existing CFR equation with an R factor of 0.6 when ethanol blends are used produces significant errors. For the catalyst durability program, a straightforward CMB approach was used to compute fuel economy, thereby allowing a straightforward evaluation of the impact of ethanol content on fuel economy. However, if an ethanol-containing fuel is to become the new certification fuel for light-duty vehicles, consistent application of the CFR equation needs to be considered for the benefit of manufacturers' CAFE compliance. The R factor is defined in more detail in Section 2 of this report.

To date, EPA has only required emissions and fuel economy testing of gasoline-fuelled vehicles with a certification gasoline that does not contain ethanol. However in 2013 EPA issued a Proposed Rule seeking comment on the establishment of an emissions certification fuel containing ethanol, such as E10 or E15.[†] The use of ethanol-containing fuel for certification will likely require changes to the Code of Federal Regulations (CFR), to allow for proper calculation of CAFE fuel economy.

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[*] Keith Knoll, Brian West, Wendy Clark, Ronald Graves, John Orban, Steve Przesmitzki, Timothy Theiss, *Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1—Updated*, NREL/TP-540-43543, ORNL/TM-2008/117, February 2009, available at http://info.ornl.gov/sites/publications/Files/Pub12154.pdf

[†] *Federal Register* Vol. 78 (98), Tuesday, May 21, 2013

2. APPROACH

2.1 VEHICLE SELECTION

Vehicles included in the R factor analysis described herein are shown in Tables 2.1 and 2.2. A total of 14 Tier 2 and 4 Tier 1/NLEV vehicle models were used for this analysis.

Table 2.1. Tier 2 vehicle models in the R factor analysis

Test site	Model year	Vehicle model	Engine family number[a]	Engine displacement (liters)	Engine configuration	Tier 2 emissions standard
Southwest Research Institute	2007	Honda Accord	7HNXV02.4KKC	2.4	I4	Bin 5
	2006	Chevrolet Silverado	6GMXT05.3379	5.3	V8	Bin 8
	2008	Nissan Altima	8NSXV02.5G5A	2.5	I4	Bin 5
	2008	Ford Taurus	8FMXV03.5VEP	3.5	V6	Bin 5
	2007	Dodge Caravan	7CRXT03.8NEO	3.8	V6	Bin 5
	2006	Chevrolet Cobalt	6GMXV02.4029	2.4	I4	Bin 5
	2007	Dodge Caliber	7CRXB02.4MES	2.4	I4	Bin 5
Transportation Research Center	2009	Jeep Liberty	9CRXT03.74PO	3.7	V6	Bin 5
	2009	Ford Explorer	9FMXT04.03DC	4.0	V6	Bin 4
	2009	Honda Civic	9HNXV01.8XB9	1.8	I4	Bin 5
	2009	Toyota Corolla	9TYXV01.8BEA	1.8	I4	Bin 5
	2005	Toyota Tundra	5TYXT04.0NEM	4.0	V6	Bin 5
	2006	Chevrolet Impala	6GMXV03.9048	3.9	V6	Bin 5
	2005	Ford F150	5FMXT05.4R17	5.4	V8	Bin 8

[a] "Engine family" and "test group" are often used interchangeably.

Table 2.2. Non-Tier-2 vehicle models in the R factor analysis

Test site[a]	Model year	Vehicle model	Engine family number	Engine displacement (liters)	Engine configuration	Emissions standard[b]
SwRI	2002	Nissan Frontier	2NSXT02.4C4B[c]	2.4	I4	NLEV/LDT1
	2002	Dodge Durango	2CRXT04.75B0	4.7	V8	Tier 1/LDT3
TRC	2003	Toyota Camry	3TYXV02.4HHA	2.4	I4	ULEV
	2003	Ford Taurus	3FMXV03.0VF3	3.0	V6	NLEV

[a] SwRI = Southwest Research Institute, TRC = Transportation Research Center Inc.
[b] LDT = light-duty truck, ULEV = ultralow emission vehicle, NLEV = National Low Emission Vehicle (Program).
LDT1–LDT3 are light truck emissions categories based on vehicle weight.
(See http://www.epa.gov/otaq/standards/light-duty/index.htm)
[c] "Engine family" on Frontier vehicles did not exactly match the EPA database for the 2002 Frontier (see ORNL/TM-2011/234).

2.2 VEHICLE AGING AND TEST PROTOCOL

Vehicles were acquired in matched sets of three or four vehicles. Matched vehicles had identical engine and transmission configuration, engine controller software, tire size, etc. Each vehicle of a set was dedicated to a specific ethanol blend for aging and emissions testing (including one dedicated to ethanol-free gasoline, or E0). Thus for a matched set of four vehicles, one vehicle was dedicated to E0, one to E10, one to E15, and one to E20. For sets of three matched vehicles, E10 was omitted. Vehicles were emissions tested at the start, middle, and end of the program, and aged on a dedicated fuel in between emissions tests. At each emissions test interval each vehicle was tested on E0 fuel and its designated ethanol blend. At each fuel change, a rigorous fuel change and adaptation protocol was followed. Details on the vehicle aging and test protocol are provided in the catalyst durability program final report.[*]

2.2.1 Aging Fuels

Aging was conducted by assigning one vehicle of each set to a fuel with a given ethanol concentration (including E0). Because the vehicles would be accruing considerable mileage and because of the relatively large number of vehicles involved in the program, it was necessary to use splash blended fuels for the aging program to reduce the fuel cost to a manageable level. For this purpose, top-tier retail gasoline[†] that did not contain ethanol was purchased locally and splash blended to produce the necessary ethanol-containing blends. SwRI acquired top-tier gasoline and splash blended it with ASTM D4806 denatured ethanol[‡] on-site to produce the 10%, 15%, and 20% ethanol blends required. TRC procured the ethanol blends from the terminal, pre-blended to the desired levels. The aging fuels were termed RE0, RE10, RE15, and RE20 to convey that they were blended using retail gasoline and to denote the nominal ethanol content of each fuel.

2.2.2 Emissions Test Fuels

The emissions test fuels were splash blends using emissions certification gasoline and ASTM D4806 denatured ethanol. TRC sourced the emissions fuel components (UTG-96 Federal Certification Gasoline and denatured ethanol) from Chevron-Phillips Specialty Chemical Company. SwRI obtained Haltermann EEE certification gasoline and ASTM D4806 denatured ethanol. The fuels were splash blended on-site at each test laboratory and subsequently analyzed to provide the fuel properties needed to support data analysis. Additional fuel analyses beyond those required for emissions tests were also performed on selected samples. These emissions test fuels were termed E0, E10, E15, and E20 to denote that they were different from the retail fuels used for vehicle aging (RE0, for example). As with the aging fuels, the octane number, RVP, and other properties of the emissions fuels varied with the ethanol content as a consequence of the splash blended nature of the fuels. Because all emissions tests were conducted at a nominal 25°C and because tracking emissions changes over time was the primary program objective, the use of splash blends in lieu of match blends was not expected to impact the results. When using match blends, certain fuel properties such as volatility and octane can be tailored to match the desired ethanol blend level. When splash blends are used, it is understood that properties such as volatility and octane will vary with ethanol content,[§,**] but it was judged by the project leadership that these variations would not

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[*] West, et al., *Intermediate Ethanol Blends Catalyst Durability Program*, ORNL/TM-2011/234,February 2012.

[†] Top-tier gasoline contains more deposit-control additives than the EPA minimum requirements (http://www.toptiergas.com/).

[‡] ASTM D4806 - *Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel*

[§] J. E. Anderson et al., “Octane Numbers of Ethanol- and Methanol-Gasoline Blends Estimated from Molar Concentrations,” *Energy Fuels* 2010, 24, pp. 6576–6585.

[**] American Petroleum Institute, *Determination of the Potential Property Ranges of Mid-Level Ethanol Blends,* Final Report, April 2010.

impact the results.* In addition, acquisition of match blends would have presented unreasonable cost and time delay burdens to the program. Some of the carbon mass fraction and heating value results came into question during the R factor analysis. Because the R factor is very sensitive to fuel properties, some adjustments were made to some fuel properties, as described in the next section.

Table 2.3 shows the relevant fuel properties for the emissions test fuels at SwRI (note that only the first five SwRI vehicle sets included E10). Each vehicle was tested with the same E0 or ethanol blend at each emissions testing interval. Table 2.4 shows the same properties for the vehicles at TRC. Because there were multiple batches of ethanol blends, Table 2.4 shows fuel properties for start-of-test, midlife test, and end-of-test. Some property values were adjusted for the R factor analysis, as described in the next two sections. All heating values were calculated from D240 (BTU/lb) and density.

Table 2.3. Emissions test fuel properties at SwRI. Shaded cells denote adjusted carbon mass fraction as discussed in section 2.2.3.

Vehicle	E0 Fuel			E10 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2007 Accord	0.869	0.744	115,495	0.831	0.748	111,491	0.815	0.752	109,656	0.792	0.754	106,727
2006 Silverado	0.869	0.743	115,138	0.829	0.751	111,296	0.812	0.751	108,849	0.794	0.752	107,213
2008 Altima												
2008 Taurus	0.878	0.742	116,328	0.832	0.748	111,707	0.817	0.751	109,844	0.795	0.752	107,269
2007 Caravan												
2006 Cobalt	0.866	0.744	114,784	Vehicles not tested on E10			0.813	0.751	109,483	0.793	0.753	107,330
2007 Caliber												
2002 Frontier												
2002 Durango	0.866	0.743	115,083				0.811	0.752	108,782	0.798	0.753	107,549

2.2.3 Adjustment of Carbon Weight Fraction for Some Fuels

The Carbon weight fraction of gasoline range fuels is normally determined by the test protocol prescribed by ASTM D5291. The volatility of gasoline and gasoline-ethanol blends can sometimes cause a loss of a small portion of the sample during the execution of the ASTM D5291 test that determines the carbon, hydrogen, and nitrogen weight fractions of the fuel. In some cases at SwRI, incomplete recovery was observed during this test, and in these cases, the carbon weight fraction was adjusted during completion of the fuel economy calculations for the FTP results. The adjustment changes the carbon weight fraction in the third decimal place (e.g., from 0.863 to 0.866). This adjustment was accomplished by summing the carbon and hydrogen weight fractions. In the event that the sum was less than 100% for an E0 fuel, a multiplication factor was computed by dividing 100 by the sum. For example, if the carbon and hydrogen weight fractions summed to 99.3%, a factor of 1.007 was computed by dividing 100 by 99.3. The carbon and hydrogen weight fractions were then both multiplied by 1.007 prior to their use in calculating fuel economy results for the FTP tests. In cases where the fuel also contained oxygen due to ethanol blending, the oxygen content was accepted as accurate and subtracted from 100 and the result divided by the sum of the carbon and hydrogen weight fractions to calculate the multiplication factor to be used to adjust the carbon and hydrogen weight fractions. Oxygen content was determined by ASTM D5599 for the SwRI fuels (and by D5622 for the TRC fuels). This procedure results in the sum of carbon, hydrogen, nitrogen, and oxygen weight fractions being 100% for each fuel and corrects the D5291 results when a loss of some

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* West, et al., *Intermediate Ethanol Blends Catalyst Durability Program*, ORNL/TM-2011/234, February 2012.

of the sample has occurred. This method inherently assumes that the speciation of the fuel sample did not change as a result of the mass loss. This adjustment was done 12 times for the SwRI fuels shown in Table 2.3.

2.2.4 Adjustment of Fuel Heating Values for Some Fuels

During analysis of the data, three heating value results from the TRC test fuels were noted to be considerably lower than expected, falling well below a line drawn through the data as shown in Figure 1. The three red data points are the results that were noted to appear inconsistent with other fuels. Since all of the ethanol-blended fuels were blended from the same batch of E0, the remaining data points (shown as blue points) were used to establish a best-fit linear correlation between heating value and fuel oxygen content. The suspect heating value results were re-computed using this relationship, resulting in increases in the heating value for these three fuels. The circles show the heating values that were used in calculations to determine R factors. For heating values that were not adjusted, the circles overlay the blue data points. For heating values that were adjusted, the circles appear vertically separated from the red data points, indicating the amount the heating value was adjusted (adjustments ranged from 63 to 194 BTU/lb$_m$, or 0.4 to 1.1%).

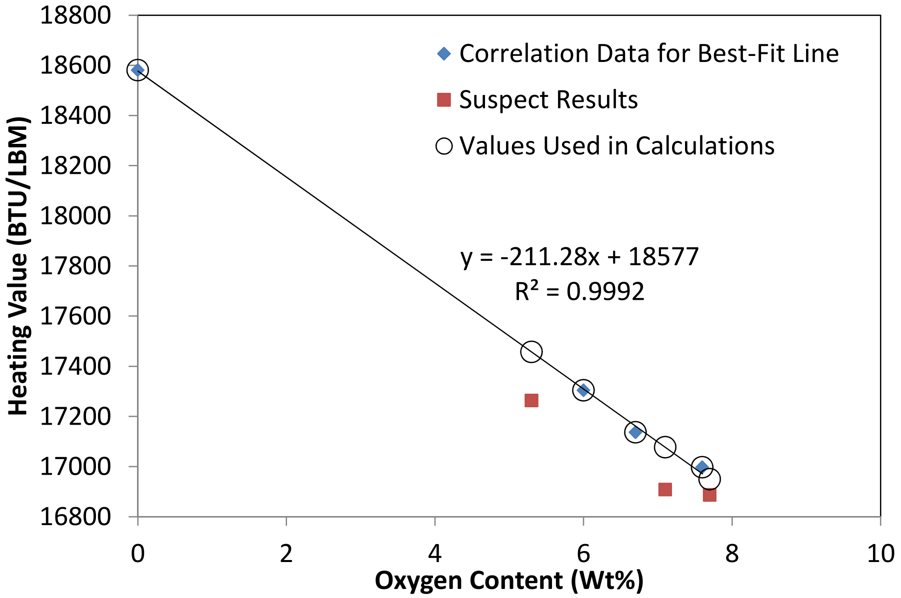

Figure 1. Heating value versus oxygen content for the TRC test fuels.

Table 2.4. Emissions test fuel properties at TRC. Shaded cells denote adjusted heating values as discussed in section 2.2.4.

Start of Test

Vehicle	E0 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2009 Civic	0.872	0.743	115,205	0.809	0.751	108,441	0.801	0.753	107,680
2009 Explorer									
2009 Corolla									
2009 Liberty									
2005 Tundra							0.792	0.754	106,648
2006 Impala									
2005 F150									
2003 Camry							0.792	0.752	106,659
2003 Taurus									

Midlife Test

Vehicle	E0 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2009 Civic	0.872	0.743	115,205	0.809	0.751	108,441	0.792	0.754	106,648
2009 Explorer									
2009 Corolla									
2009 Liberty									
2005 Tundra							0.792	0.752	106,659
2006 Impala									
2005 F150									
2003 Camry							0.795	0.752	106,910
2003 Taurus				0.813	0.749	109,111	0.797	0.752	107,161

End of Test

Vehicle	E0 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2009 Civic	0.872	0.743	115,205	0.809	0.751	108,441	0.792	0.752	106,659
2009 Explorer									
2009 Corolla				0.813	0.749	109,111	0.797	0.752	107,161
2009 Liberty									
2005 Tundra									
2006 Impala									
2005 F150									
2003 Camry									
2003 Taurus									

2.3 R-Factor Analysis Approach

2.3.1 R Factor Definition

As discussed previously, the R factor is a value that describes change in fuel economy that accompanies a change in the volumetric heating value of the fuel being used. For example, when ethanol is blended with gasoline, the heating value of the blend is reduced compared with the gasoline before blending. This reduction is a result of the presence of ethanol, which has a lower volumetric heating value than gasoline. The R factor is defined according to the following equation.

$$R = \frac{\left(\frac{VOLFEi}{VOLFEr}\right) - 1}{\left(\frac{VOLHVi}{VOLHVr}\right) - 1}$$

VOLFE is the volumetric fuel economy result in miles per gallon for either the test fuel (subscript i) or the reference fuel (subscript r), and VOLHV is the volumetric heating value for the fuels in BTU per gallon, using the same subscripts as for the volumetric fuel economy. Using this form, R can also be expressed as the percent change in volumetric fuel economy using a test fuel compared to a result with a reference fuel divided by the percent change in the volumetric heating value of the test fuel compared to the volumetric heating value of the reference fuel.

2.3.2 R Factor Determination

The fuel economy data were analyzed for each vehicle that was tested using both a fuel that did not contain ethanol and a fuel that was blended with ethanol. During each emissions test interval for each vehicle, the average fuel economy with E0 was calculated and compared with the average fuel economy for the same vehicle tested using an ethanol blended fuel. As an example, consider the determination of R for a 2009 Ford Explorer, tested at the start-of-test emissions interval. Two such vehicles were tested using an ethanol-blended fuel: one using E15 and the other using E20. The average fuel economy for the E15 vehicle when tested using E0 and when tested using E15 was determined. These data were then used to compute an R value for the E15 2009 Ford Explorer at the start-of-test emissions interval. Similarly, the average fuel economy data were computed for the E20 vehicle and an independent R value computed for this vehicle. In this way, vehicle-to-vehicle variations in baseline fuel economy using E0 were removed from the analysis. Similarly, the R values were assessed for these vehicles at the other emissions test intervals, which removed any affect of vehicle aging on the baseline fuel economy from the R factor analysis. This approach was repeated for each vehicle and each emissions test interval.

Following determination of the individual R factors for each vehicle at each emissions test interval, the R factors were pooled to determine characteristic average values for different vehicle groups.

3. RESULTS

3.1 R Factor Values

3.1.1 Vehicle-Specific R Factors

The R factors that were computed for each vehicle model were averaged to produce an overall average R factor for that model. Because in some cases 2 vehicles (E15 and E20) or 3 vehicles (E10, E15, and E20) were tested at each of three emissions test intervals, a maximum of 9, and in most cases only 6 R factor values could be pooled for each vehicle. As such, the confidence intervals for the vehicle-specific R factors are relatively large. The vehicle-specific R factors are shown in Figure 2. Though the average values show considerable variation, many of the 95% confidence intervals overlap, indicating that much of the variation may be explained by test-to-test variability. The 95% confidence intervals reported herein are calculated based on the scatter in the fuel economy results. Additionally, there is uncertainty present in the ASTM results for heating value, carbon weight fraction, and specific gravity that have not been included in the confidence intervals. Inclusion of these uncertainties would increase the confidence intervals.

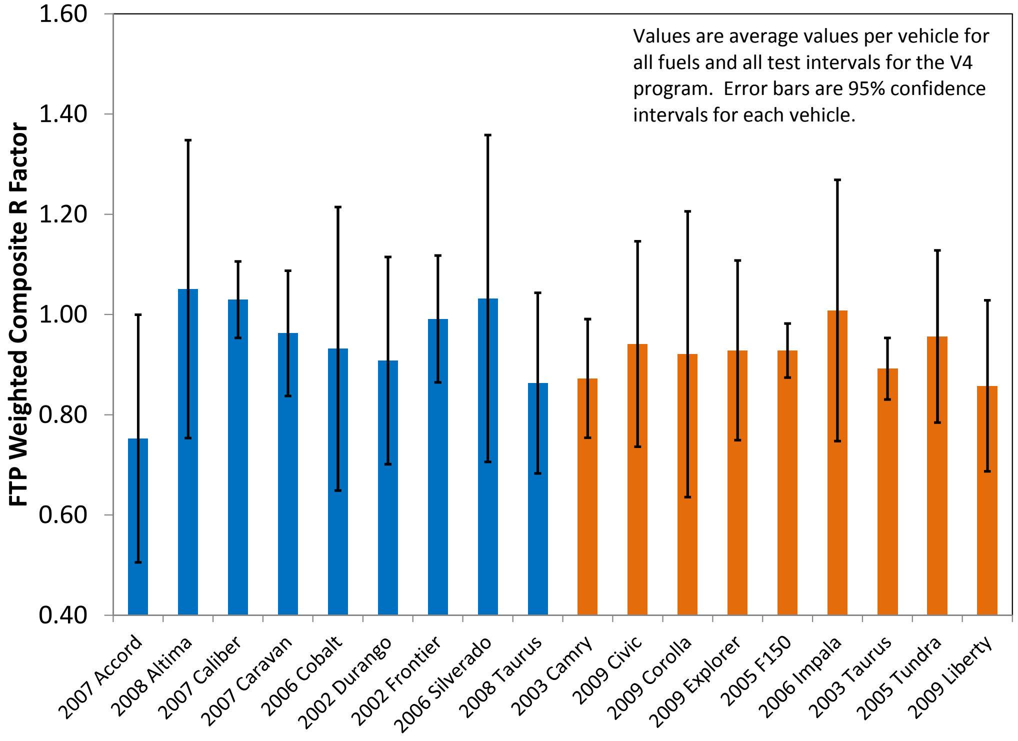

Figure 2. Average R factor for each vehicle model.

3.1.2 Average R Factor Values for Fleets

The data were pooled to analyze the vehicles in four fleets: the SwRI Test Fleet, the TRC Test Fleet, the Total Test Fleet, and the Tier 2 Test Fleet. Additionally, the data were pooled to allow analysis of the impact of fuel ethanol content, if any, on the R factor. These results are shown in Figures 3 and 4.

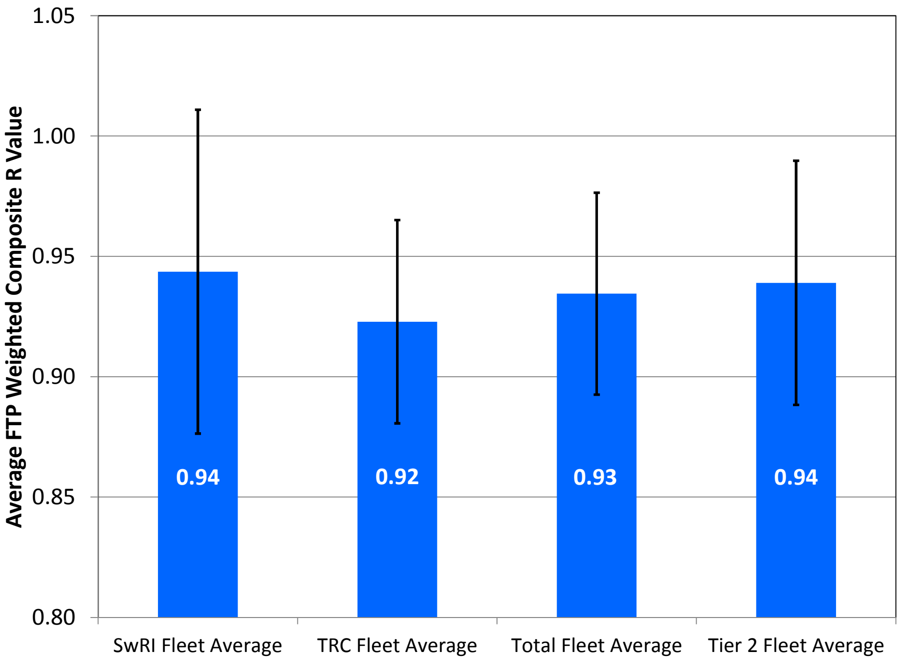

Figure 3. Fleet average R factor values with 95% confidence intervals.

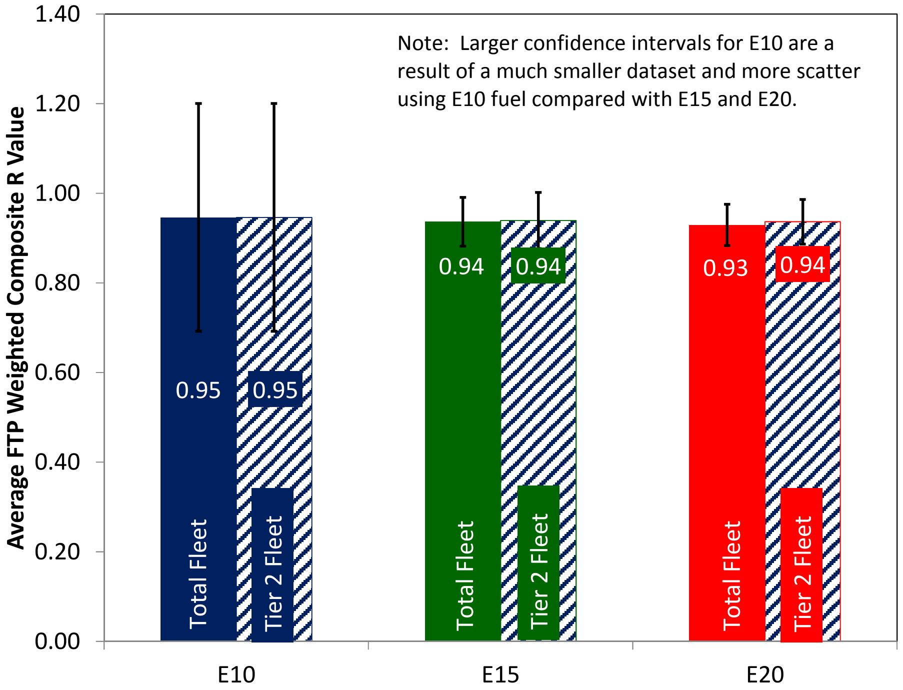

Figure 4. Fleet average R factor values for ethanol-blended fuels with 95% confidence intervals.

During the R factor analysis, some of the fuel economy results for the 2007 Honda Accord were questioned. The FTP fuel economy results showed unexpected variability that resulted in R factors that were deemed to be illogical and unrepeatable. No single issue with the data could be firmly established, however. Thus, the fleet average analyses were completed both with the Accord data included, as has previously been presented, and also with the Accord data omitted, as shown in Figures 5 and 6.

Removing the Honda Accord data had the effect of marginally increasing fleet averages that had previously included the Accord data, and also marginally impacting the 95% confidence intervals.

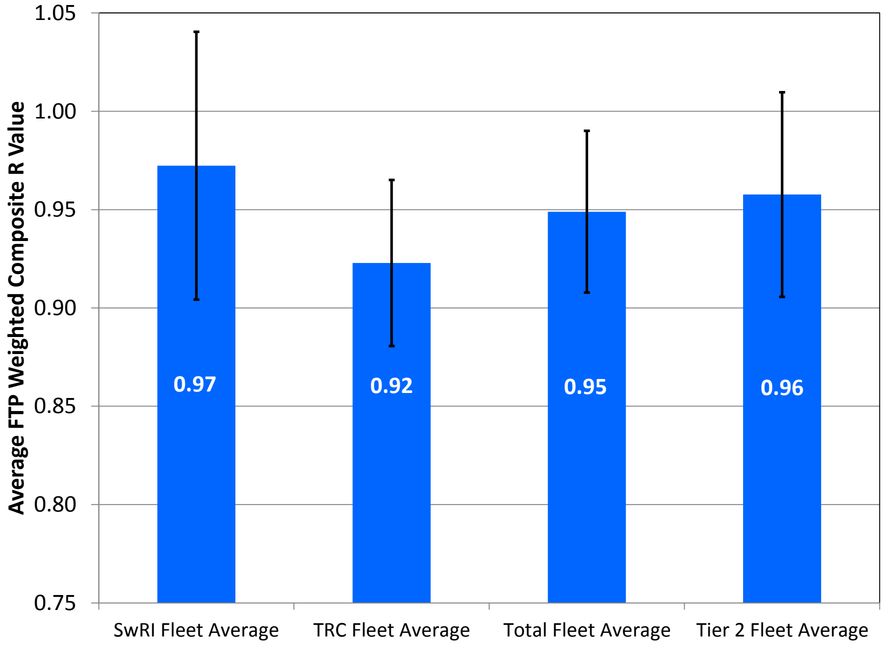

Figure 5. Fleet average R factor values with 2007 Honda Accord results omitted.

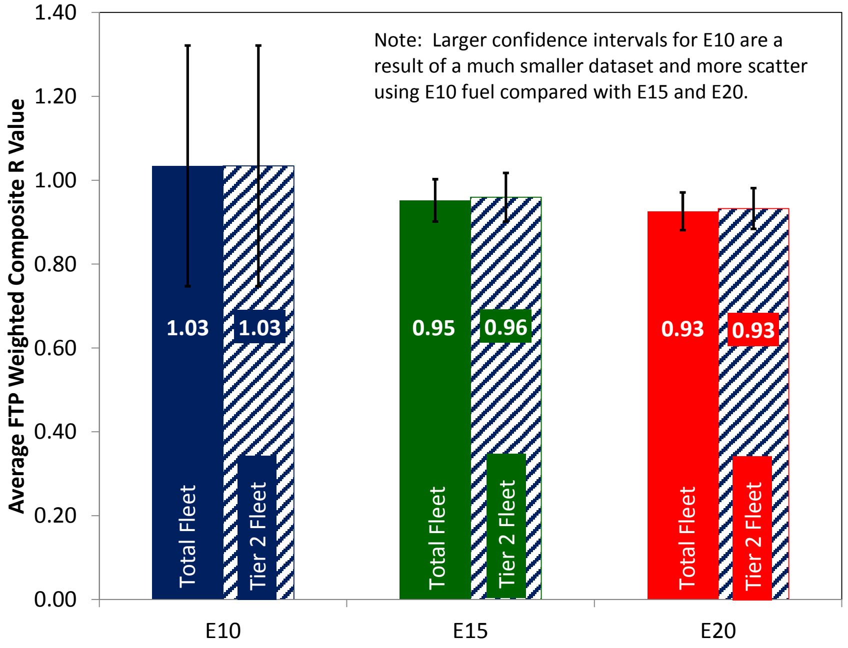

Figure 6. Fleet average R factor values for ethanol-blended fuels with 2007 Honda Accord results omitted.

4. CONCLUSIONS

The calculated R factor for the DOE catalyst durability study vehicles is 0.94 ±0.04 (or 0.96±0.04 with one problematic vehicle omitted). Within error limits, these results are the same as those obtained in the 1993 Auto/Oil study. The current factor of 0.6 which is called out in CFR is clearly too low, and a proper factor for modern vehicles is closer to unity, as might be expected from improved air/fuel ratio control common for more modern vehicles. Future work to establish the correct R factor should consider additional test cycles as well as the potential for high-efficiency technologies that may be impacted by fuel characteristics other than the heating value (the R factor could vary by test cycle and/or with vehicle technology).

APPENDIX A.
BIBLIOGRAPHY OF INTERMEDIATE ETHANOL BLENDS STUDIES

APPENDIX A. BIBLIOGRAPHY OF INTERMEDIATE ETHANOL BLENDS STUDIES

The following reports and websites relate to Intermediate Ethanol Blend Studies supported or partially supported by the Department of Energy since 2007; also listed are relevant EPA and Coordinating Research Council websites. Numerous oral presentations were given throughout the program; these are not listed, however those given at DOE Annual Merit Reviews are included here.

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